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THE UNIVERSITY OF ALBERTA

THE USE OF A NETWORK ANALYSER IN STUDYING

RESTRIKING VOLTAGE TRANSIENTS

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES

IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE

DEPARTMENT OF ELECTRICAL ENGINEERING

by

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ABSTRACT

The voltage appearing across a pole of a power circuit breaker immediately following current interruption is known as Restriking Voltage. It is a transient which depends on system conditions, fault conditions and on characteristics of the breaker itself. In the past thirty years much research has been expended in an attempt to establish the severity of restriking voltage on circuit breakers and methods of including this factor in circuit breaker specifications. The transient has its worst effect in the case of air blast circuit breakers. Fortunately, air blast breakers have less effect on the transient than do other breaker types. Therefore, a study of "inherent" system transient characteristics is of interest.

One method of study is by means of a Network Analyser on which the system is represented in miniature. Normally, however, a Network Analyser is designed to be accurate at only one frequency, namely its base frequency. Transients sometimes contain component frequencies of 1000 times the base frequency. The purpose of the paper is to prove that, with proper precautions, the University of Alberta's Contraves Network Analyser can be used for studies of this type.

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1. The first part of the paper is devoted to a general
discussion of the problem. It is shown that the
problem is of great importance in the theory of
differential equations. The second part of the paper
is devoted to a detailed study of the problem.
It is shown that the problem is of great importance
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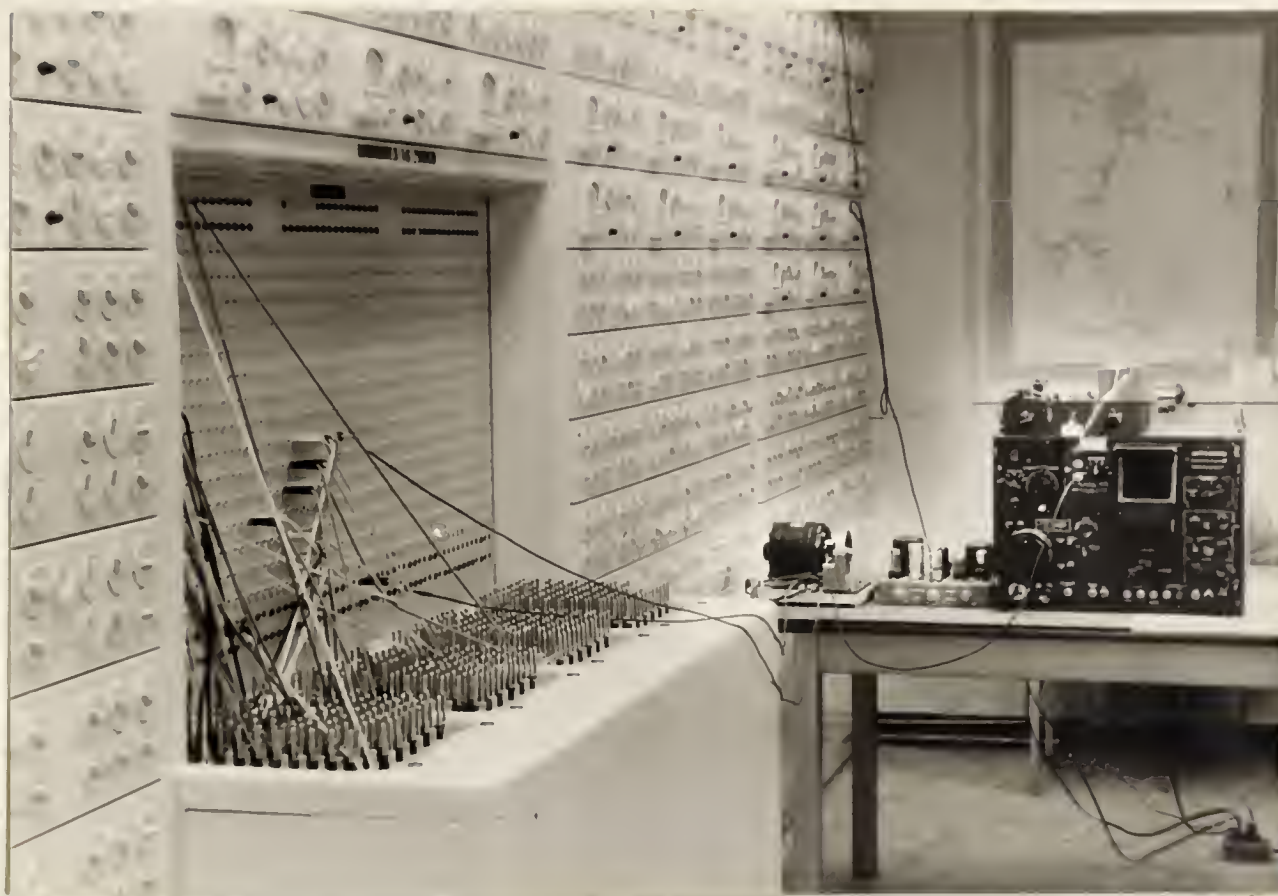
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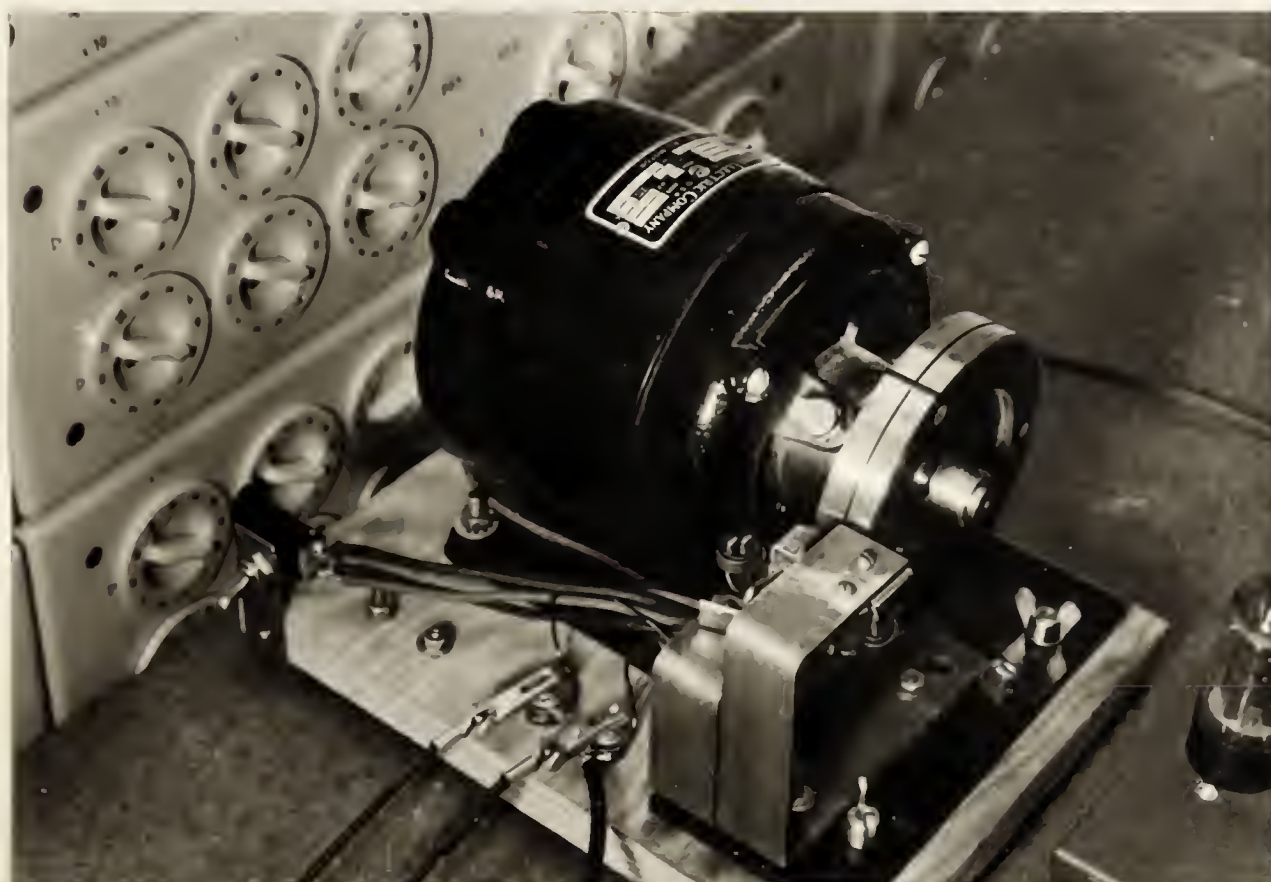
"CONTRAVERS"
NETWORK ANALYSER
(left)

&

SPECIAL APPARATUS
FOR TRANSIENT STUDIES
(on table)



CLOSE-UP OF SYNCHRONOUS SWITCH





Chapter I - PREAMBLE

The terms "Restriking Voltage" and "Recovery Voltage" as used herein, are defined as follows:

Restriking Voltage - That voltage which, as a function of time, appears across the contacts of one pole of a circuit breaker when it interrupts a current.

Recovery Voltage - The power frequency component of the Restriking Voltage.*

When a D.C. current is interrupted, the voltage across the switch and current through the switch vary as shown in Figure 1.

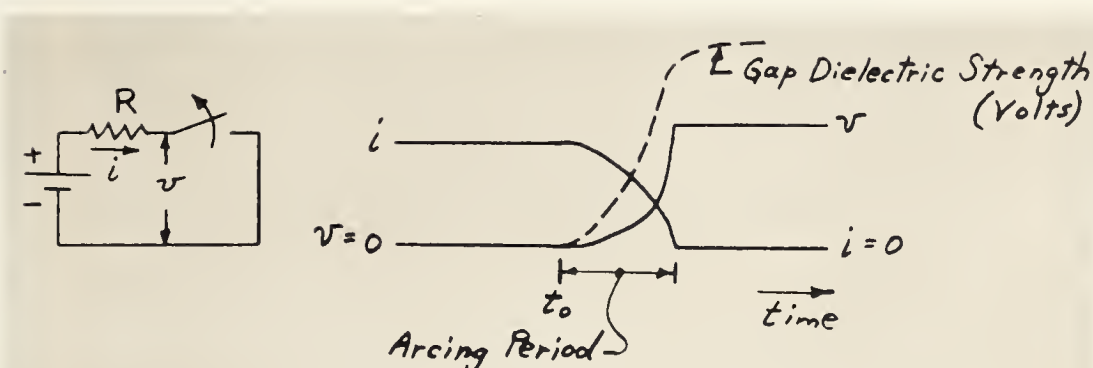


Fig. 1 - D.C. Arc Interruption Conditions

A criterion for successful interruption is that the dielectric strength of the gap between contacts (dashed line in Fig. 1) rises faster than does the voltage across the gap. If it does not, the gap will "restrike" and hence the voltage appearing across the gap is called the Restriking Voltage.

*In the past, "Restriking Voltage" as here defined has often been called "Recovery Voltage" or "Transient Recovery Voltage". The definition used herein is recommended by C.I.G.R.E.

For an A.C. circuit, the conditions are as shown in Figure 2.

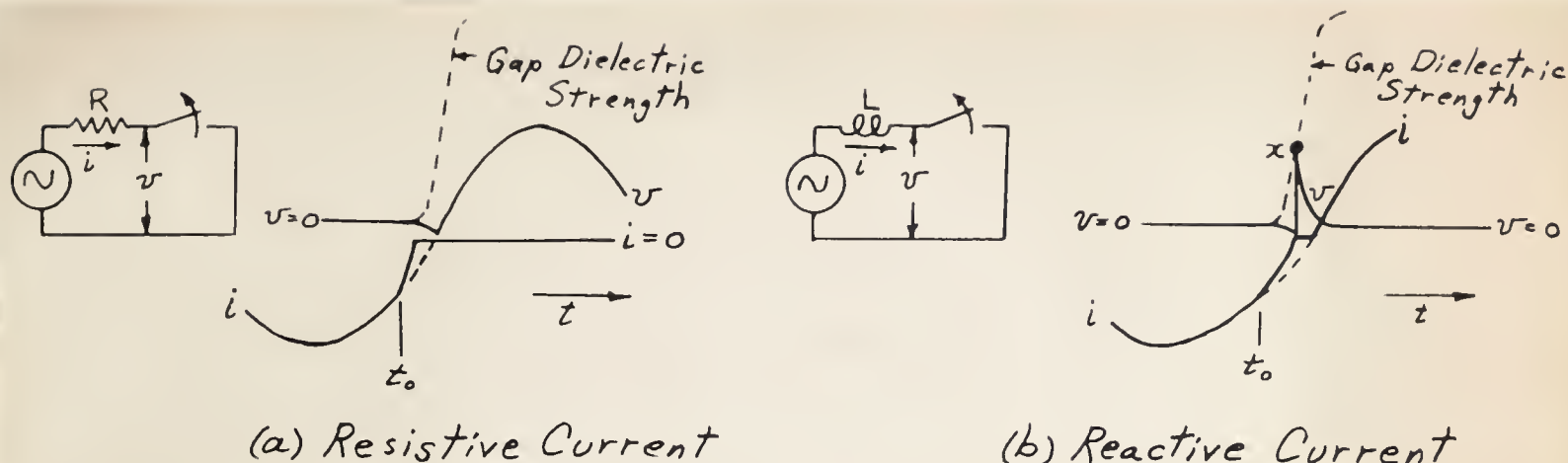


Fig. 2 - A.C. Arc Interruption Conditions

It should be noted that an A.C. circuit breaker (or switch) always interrupts a heavy current close to a normal current zero. This is because a practical circuit breaker drawing a heavy arc out to its critical length* moves relatively slowly compared to the normal sine wave decay of current to a "natural" zero. This is not true for light currents, such as transformer magnetizing currents, and this represents a problem not specifically dealt with in this paper.

As seen in Figure 2(b), interruption of an inductive current represents a severe condition. This is because the voltage (leading the current by 90°) is at a peak immediately upon interruption of the current, near a normal current zero. Since the restriking voltage curve crosses the dielectric strength curve, at "x", the gap will restrike and interruption has not been successful. After this restrike, however,

*Critical arc length: The length at which a given arc will extinguish spontaneously.

successful interruption may occur, since the contacts will be further apart, and arc conditions therefore more favourable. However, the repeated arc-extinguish-restrike cycle may cause damage to a particular breaker under particular conditions. For example, a bulk oil breaker will quite normally undergo this cycling for five or six half-cycles whereas an air blast breaker should not restrike, i.e., should interrupt at the first current zero after the contacts have started to part.

The condition is modified if there is capacitance-to-ground near the breaker, as shown in Figure 3.

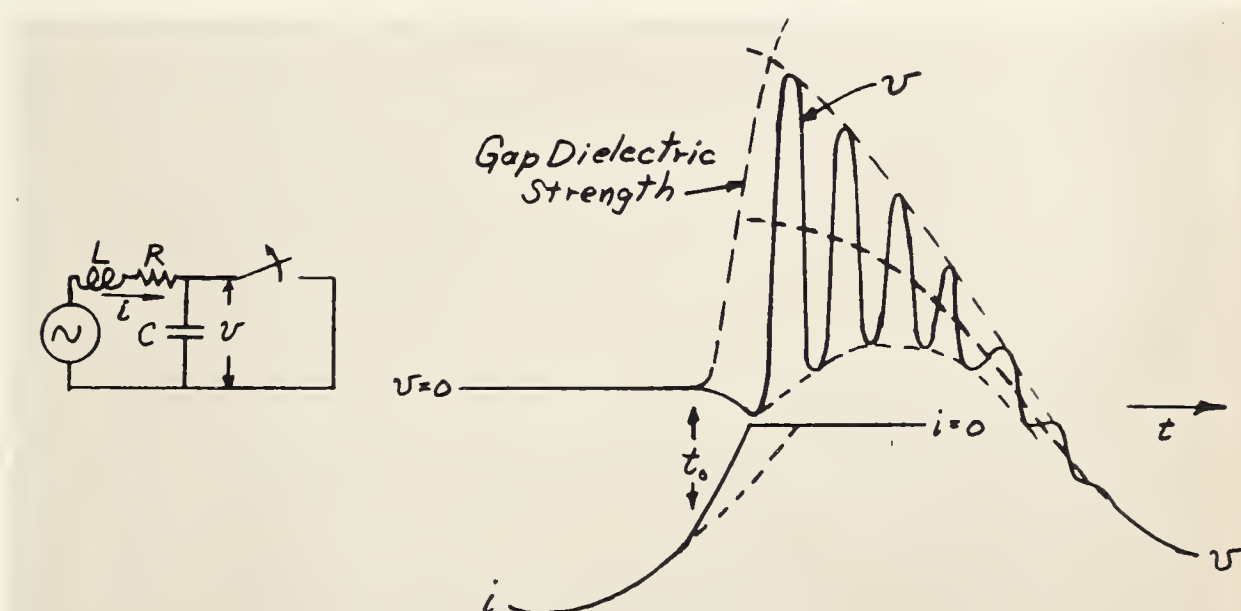


Fig. 3 - Typical Restriking Voltage Transient

The frequency of the oscillation observed in Figure 3 is called the Natural Frequency and is given by

$$f = \frac{1}{2\pi\sqrt{LC}}$$



The oscillation is exponentially damped by resistance in the circuit. Comparison of Figures 2 and 3 reveals that the presence of capacitance has two effects:

(1) It alleviates the condition, in that the voltage across the capacitor, and hence across the breaker, cannot rise immediately, but instead rises in accordance with the natural frequency.

(2) It aggravates the condition, in that a voltage up to double the normal peak voltage plus arc voltage ($2\sqrt{2}V_{rms} + E_a$) can appear.

In general, then, a high frequency, lightly damped oscillation can cause trouble. It should be noted that the "doubling" effect can be more than double for certain types of faults and for interruptions away from a normal current zero (current chopping). Current chopping can only occur in practice when very light currents are being interrupted. Under such conditions voltages of at least five times normal are common.

If the circuit of Figure 3 is replaced by an actual power system network, Figure 4 might be a typical result. Note that capacitances are shown in the network in places where they are normally neglected, since small capacitances

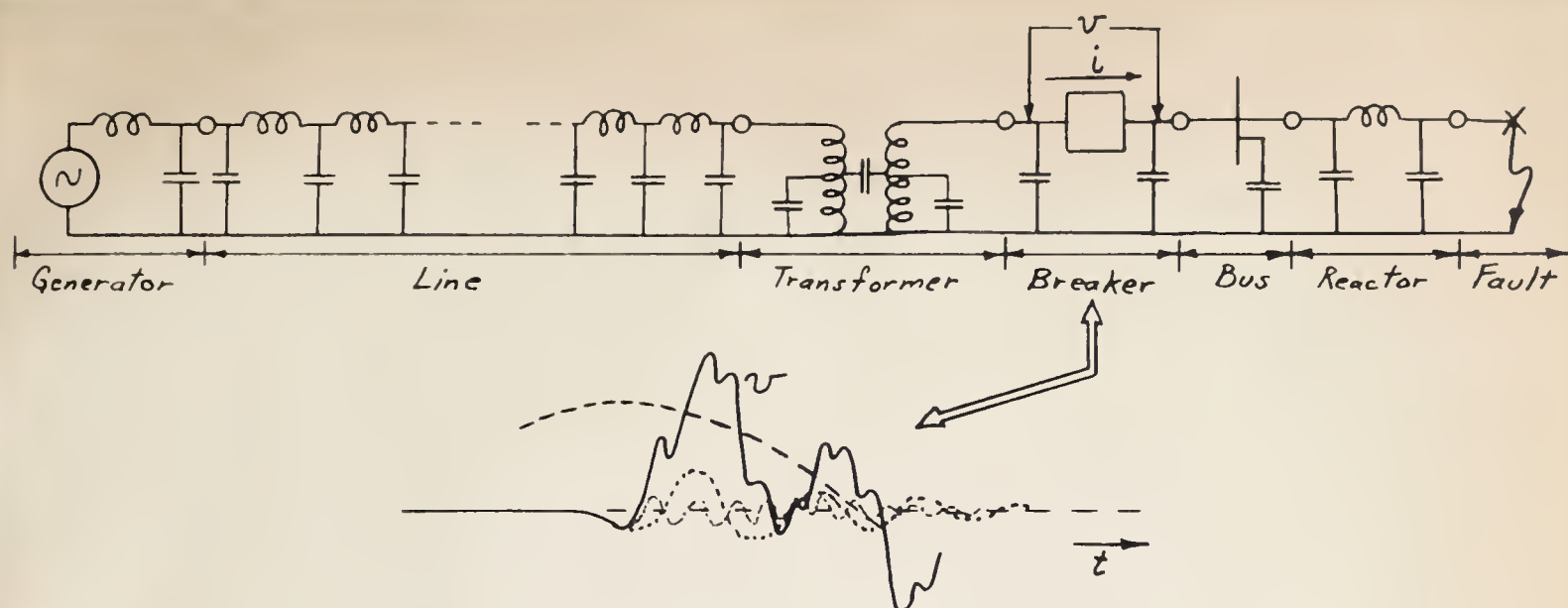


Fig. 4 - Possible System High Frequency Representation and Result

materially affect the high frequency oscillations. Other complications of the circuit will be mentioned later. In Figure 4 the restriking voltage curve has a multiple frequency character, since there are many LC combinations in the circuit. Two component frequencies have been sketched in.

The shape and magnitude of the curve is affected by several things:

(1) Circuit constants L , C , and R . - As previously mentioned, LC combinations govern the frequency of oscillation, and R produces damping.

(2) System prevailing conditions - If circuits near the breaker having high capacitance (such as lines or cables) happen to be disconnected from the bus at the time of the fault, oscillation frequencies will tend to be much higher.

(3) Type of fault - It can be shown that the first phase

to clear a three-phase ungrounded fault normally encounters the worst condition. The restriking voltage transient under this condition is superimposed on 1.5 times the normal voltage wave crest, which is $\sqrt{2}V_{\text{rms}}$ per phase.

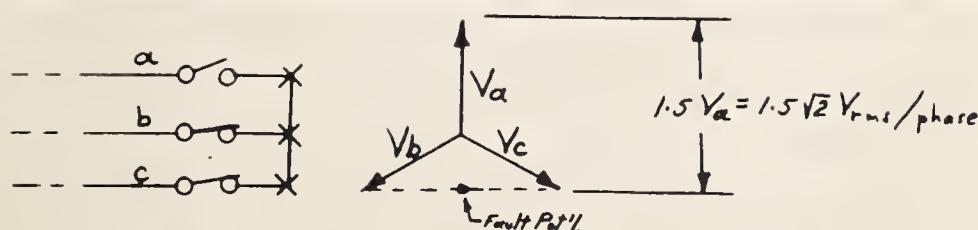


Fig. 5 - Three-Phase Ungrounded Fault

(4) Point of interruption in the current wave - As previously mentioned, current chopping can cause severe transients, but this does not happen for heavy fault currents.

(5) Circuit breaker itself -

(a) Post-arc conductivity. After the arc is extinguished, ionized gases are still present, and constitute a resistance in the circuit, with resultant damping of the transient.* The effect is usually considered small, and authors do not agree as to its theoretical meaning. In bulk oil breakers, the effect is large enough to severely damp the high frequencies, and these breakers are therefore "self-protecting" in a sense.

*See Ref.#1, page 181, for an extensive bibliography on this.

(b) Oil breakers with "arc control pots" have an opposite, exaggerating effect on the transient, but their speed of recovery is high enough to make them inherently insensitive to the restriking voltage problem.*

(c) Air blast breakers are closer to being "ideal switches". (An ideal switch changes from zero ohms impedance to infinite ohms impedance in zero time.) They are therefore sensitive to system inherent restriking voltage transients. This is one reason for extensive practical interest in the subject.

The severity of a particular restriking voltage is hard to define, since it must be compared with a breaker's dielectric strength recovery curve, and such curves are very elusive. The latest suggestion of C.I.G.R.E.[†] is to define two points which are on the transient and its envelope. See Figure 6. This is called the "method of four parameters"

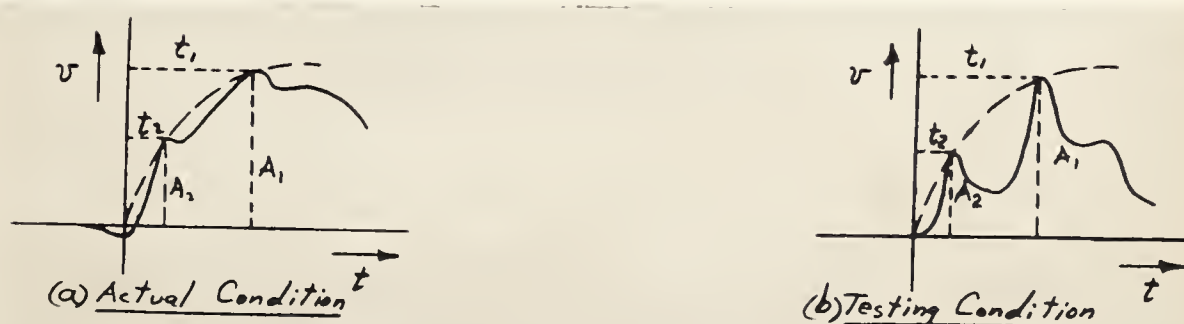


Fig. 6 - Method of Four Parameters

*See Ref.#2, page 102.

[†]C.I.G.R.E. Study Committee No.3. Ref.#6.

the parameters being A_1 , t_1 , A_2 , and t_2 , and is proposed as a basis for setting up testing station circuits to simulate actual system conditions. Thus a testing station producing the transient of Figure 6(b) would be considered to have reproduced the actual condition of Figure 6(a).

Two methods of curve definition still in common use, employ only two parameters:

Method 1 - "Natural Frequency" and "Amplitude Factor"

Method 2 - "Rate of Rise of Restriking Voltage" and
"Amplitude Factor".

See Figure 7.

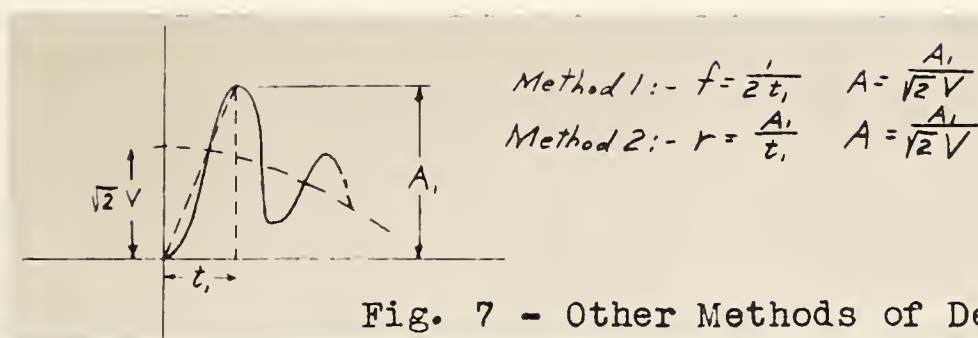


Fig. 7 - Other Methods of Description

Both of these methods suffer from the disadvantage of ambiguity when more than one component frequency is present.

The A.S.A. standard on the subject (C37.4-1953) states--

"Transient Recovery Voltage Rate is the rate at which voltage rises across the terminals of a circuit interrupting device upon interruption of the current. It is usually determined by dividing the voltage at one of the

crests of the transient recovery voltage by the time from current zero to that crest."

Chapter II - HISTORY OF INVESTIGATIONS

Since 1920, some 200 articles have been written by about 130 authors, on the subject of restriking voltage. An extensive chronological bibliography giving a summary of each article can be found in Chapter H of Reference #1. It is complete up to 1946, prior to which most of the fundamental work on the subject was done.

In about 1952 a group known as "Study Committee No. 3" was formed within the C.I.G.R.E. organization, to study "High Tension Switching and Circuit Breakers". Ten European countries as well as Canada and the U.S.A. are members of the Committee, and about 40 technical reports have been submitted to the Committee.* Their main concern in the field of restriking transients has been to find:

- (1) What are the actual network circuit breaker stresses?
- (2) How these can best be duplicated in a testing station,
- (3) How they can best be written into circuit breaker specifications.

With regard to point number (1) above, there are three practical methods of determining the actual network stresses:

- (1) By calculation

*Copies of these are on file in Prof. J.A. Harle's office at the University of Alberta.

(2) By tests on the network itself

(3) By tests on a Network Analyser.

Unfortunately, none of these has yet been used to satisfactorily take into account the effect of the circuit breaker itself on the transient. As previously stated, however, the transient has its most pronounced effect on air blast breakers, and luckily, air blast breakers have a minimum effect on the transient. Thus the present study applies mainly to the application and selection of air blast breakers, and is concerned with the suitability of the University of Alberta's Contraves Network Analyser for this type of study.

Chapter III - MATHEMATICAL APPROACHES

While the purpose of using the Network Analyser is to circumvent the need for excessively complicated mathematical solutions (in the same way as for power frequency problems), a mathematical treatment of the simpler cases met in practice is desirable for various reasons:

- (1) To gain insight into how the various network elements affect the transient, and
- (2) To check results obtained for test cases represented on the Analyser.

Also, simple cases may sometimes be more easily calculated than solved by other methods.

A. Simplest Case - Single Frequency Transient

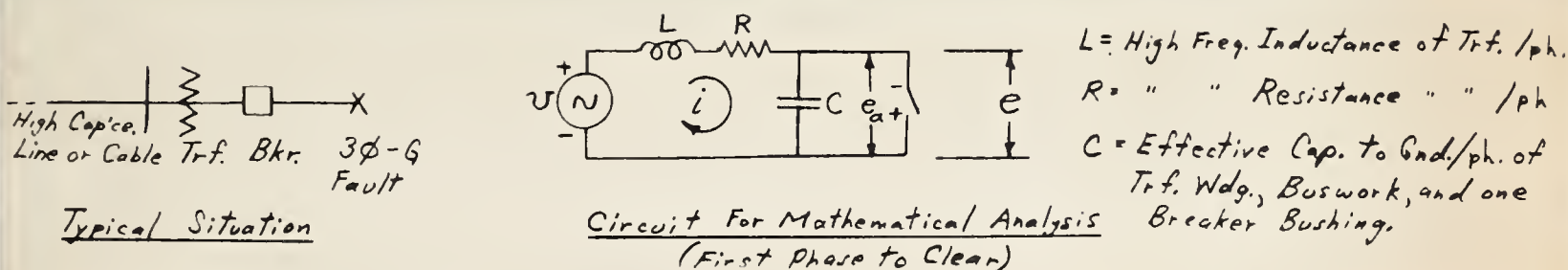


Fig. 8 - Condition for Single Frequency Transient

The circuit above is best solved by Laplace Transforms.

The solution is

$$e = v - \frac{\omega}{\omega_n} (v - e_a) e^{-\xi \omega t} \sin(\psi - \omega_n t)$$

where: symbols are defined on following page.

e = restriking voltage

v = peak value of recovery voltage (assumed constant during interval of interest)

e_a = arc voltage

$$\omega = \frac{1}{\sqrt{LC}}$$

$$\omega_n = \sqrt{1 - 2} \cdot \omega$$

$$\xi = \frac{R\sqrt{C}}{2\sqrt{L}}$$

$$\psi = \tan^{-1} \sqrt{\frac{4L}{R^2C} - 1}$$

The result is plotted in Figure 9.

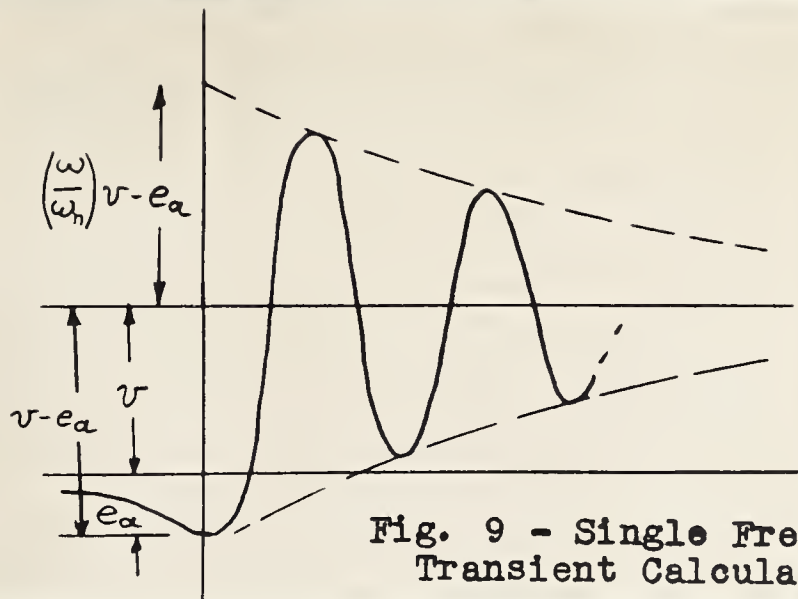


Fig. 9 - Single Frequency Transient Calculation

B. Double Frequency Transient

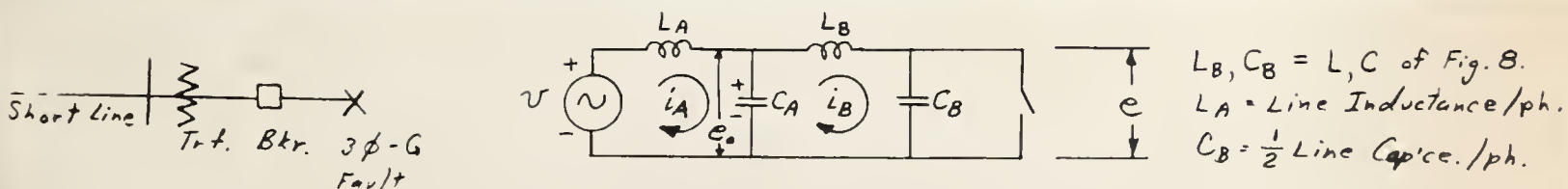


Fig. 10 - Condition for Double Frequency Transient

In this case arc voltage and circuit resistance have been

ignored, to avoid unnecessary complications. The result is

$$e = v \left(1 - \frac{1}{\omega_S^2 - \omega_R^2} \right) \left[(\omega_S^2 - \omega_{AB}^2) \cos \omega_R t + (\omega_{AB}^2 - \omega_R^2) \cos \omega_S t \right]$$

$$\text{where: } \omega_R^2 = \frac{\omega_B^2 (\omega_{AB}^2 + \omega_A^2)}{2\omega_{AB}^2} - \sqrt{\frac{\omega_B^2 (\omega_{AB}^2 + \omega_A^2)}{2\omega_{AB}^2}^2 - \omega_A^2 \omega_B^2}$$

$$\omega_S^2 = \quad \quad \quad + \quad \quad \quad "$$

$$\omega_A^2 = \frac{1}{L_A C_A}$$

$$\omega_B^2 = \frac{1}{L_B C_B}$$

$$\omega_{AB}^2 = \frac{1}{(L_A + L_B) C_B}$$

Hammarlund (Reference No. 1) has drawn two sets of curves which allow very quick determination of the two transient frequencies and their relative amplitudes, from given circuit constants. That is, f_R , f_S , a_R , and a_S from L_A , C_A , L_B , and C_B . These curves are reproduced in Figure 11. An additional chart, useful in finding the frequency corresponding to any L and C is shown in Figure 12. Values different from those lying within the chart's range can be deduced by proportioning.

An example of the use of these charts follows:

Given	Compute (Follow instructions in Fig. 11)	
$L_A = 34.6 \text{ mH}$	$f_A = 240 \text{ cps}$	$a_R = 0.59$
$C_A = 12.7 \text{ } \mu\text{F}$	$f_B = 300 \text{ cps}$	$a_S = 0.41$
$L_B = 146 \text{ mH}$	$\alpha = 1.25$	$f_R = 209 \text{ cps}$
$C_B = 1.98 \text{ } \mu\text{F}$	$\beta = 0.237$	$f_S = 343 \text{ cps}$
	$k = 1.28$	
	$f_M = 268 \text{ cps}$	

The curves are simple to use, the procedure being as follows

a. Simplify the circuit to any of the types shown in table 1

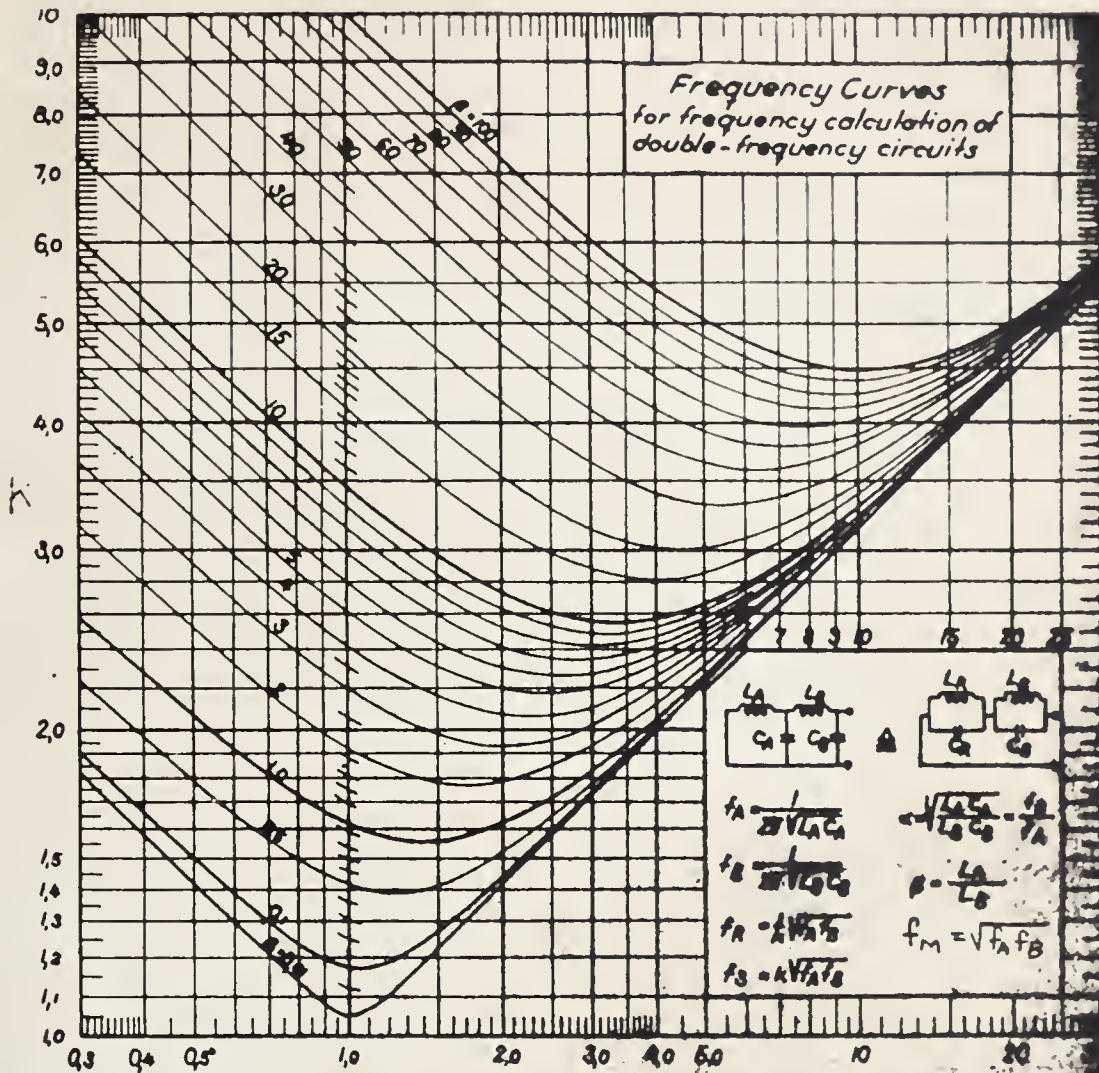
b. Compute α , β and $f_M = \sqrt{f_A f_B}$

c. Find k from the frequency curves; then compute

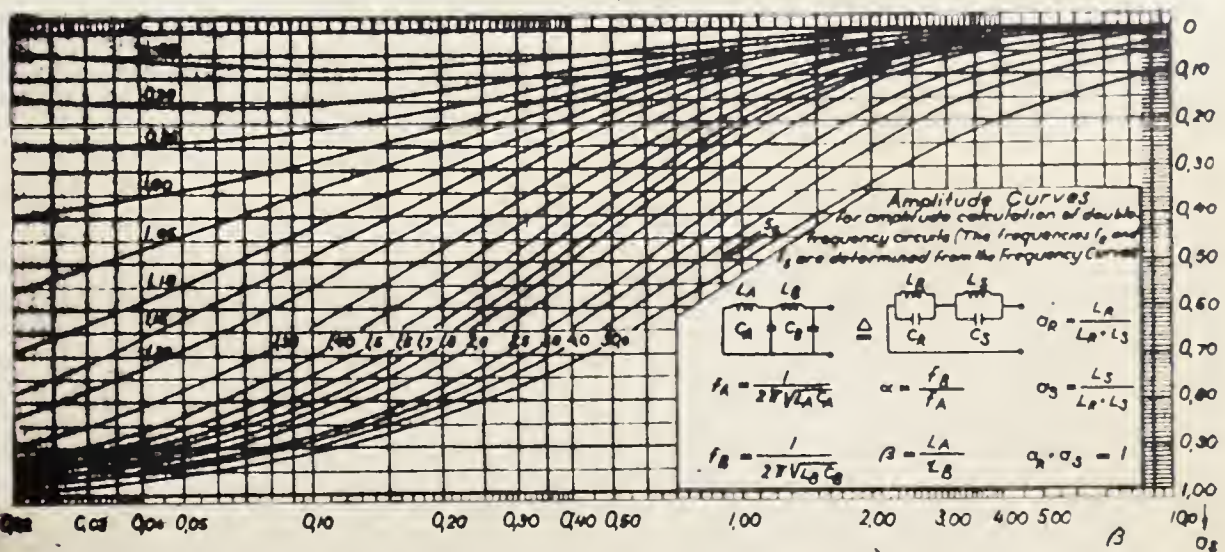
$$f_R = \frac{1}{k} f_M$$

d. Find the relative amplitudes a_S and a_R from the amplitude curves

e. The rate of rise is most conveniently obtained by plotting the oscillation graphically, damping may then be taken into account



Curves for frequency computation of two-frequency circuits.



Curves for amplitude computation of two-frequency circuits.

$$a_R = 1 - a_S$$

FIG. 11 - Reprinted from Reference No.1



$$f = \frac{1}{2\pi\sqrt{LC}}$$

C. More Complicated Transients

Hammarlund has pursued the subject mathematically for a great number of possible circuit configurations.* Many of his calculated curves agree well with actual oscillograms recorded on the Swedish system. The computations are mathematically rigorous but still necessarily involve circuit approximations. As the author points out, it takes a good deal of practice before one can sense when and what approximations are justified.

An A.I.E.E. article by Adams, Reference No.4, gives a detailed mathematical calculation for a breaker interrupting a line fault, with a current-limiting reactor between the breaker and the line. This situation (breaker adjacent to reactor or transformer) usually leads to severe high frequency transients, because the capacitance-to-ground between the breaker and circuit reactance, is very small.

D. Effect of Resistance (Damping)

There are three common methods of describing damping. They are defined as follows: (Refer to Fig.13)

(1) Crest Ratio, of Amplitude Factor = $1 + a$

(2) Decrement Factor = $\frac{a}{b}$

(3) Damping Ratio $\doteq \frac{1}{2\pi} \log \frac{a}{b}$

*See Ref. #1, Chapter B-IV.

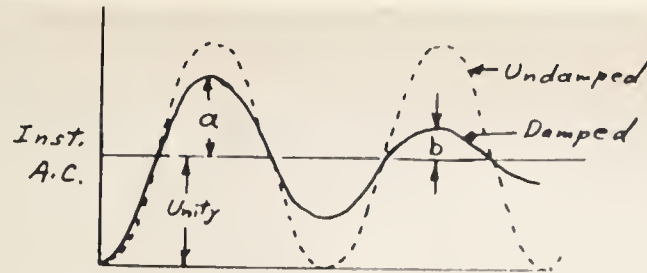


Fig. 13 - Single Frequency Transient

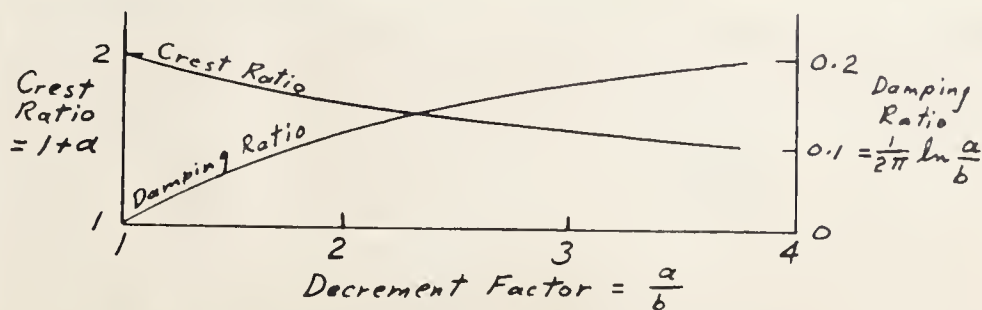


Fig. 14 - Comparison of Damping Terminology

Relations between the three methods are shown in Figure 14.

The first two methods are useful from the point of view of quick determination from an observed wave form, or for application to a calculation in which resistance has been neglected. The third is useful in mathematical analyses where resistance is included. In applying damping to a calculated wave, a Crest Ratio of 1.6 appears to be reasonable for most practical purposes. This corresponds to a Damping Ratio of 0.15 and a Decrement Factor of 2.8.

If more than one frequency exists in the transient, each will have its own characteristic damping, but for simplicity they are usually considered equally damped.

On high voltage lines, corona will also be a factor in damping, especially if one must consider waves reflecting back and forth on a long transmission line.

E. Recovery Voltage (Power Frequency)

The restriking Voltage may be thought of as an oscillation "seeking" the recovery voltage, overshooting as discussed in Section D, by a factor of up to 2.0 and usually about 1.6. Thus the magnitude of the recovery voltage is important. Several important factors enter into it,* the most important of which is the type of fault. If the zero sequence impedance equals the positive and negative sequence impedances (the system and fault are solidly grounded) the recovery voltage will be equal to the voltage before the fault. However, as shown by the curves of Figure 15, high recovery voltages can occur when the zero sequence impedance is, for example, capacitive; i.e., $\frac{X_0}{X_1}$ is negative. As shown, in rare circumstances, conditions can occur to give recovery voltages of at least 4 times normal. The most common recovery overvoltage, however, is 1.5 times normal phase-to-neutral crest, which appears across the first phase to clear an ungrounded fault. In this case, the zero sequence

*See Reference No.3, page 146.

impedance of the system is high.

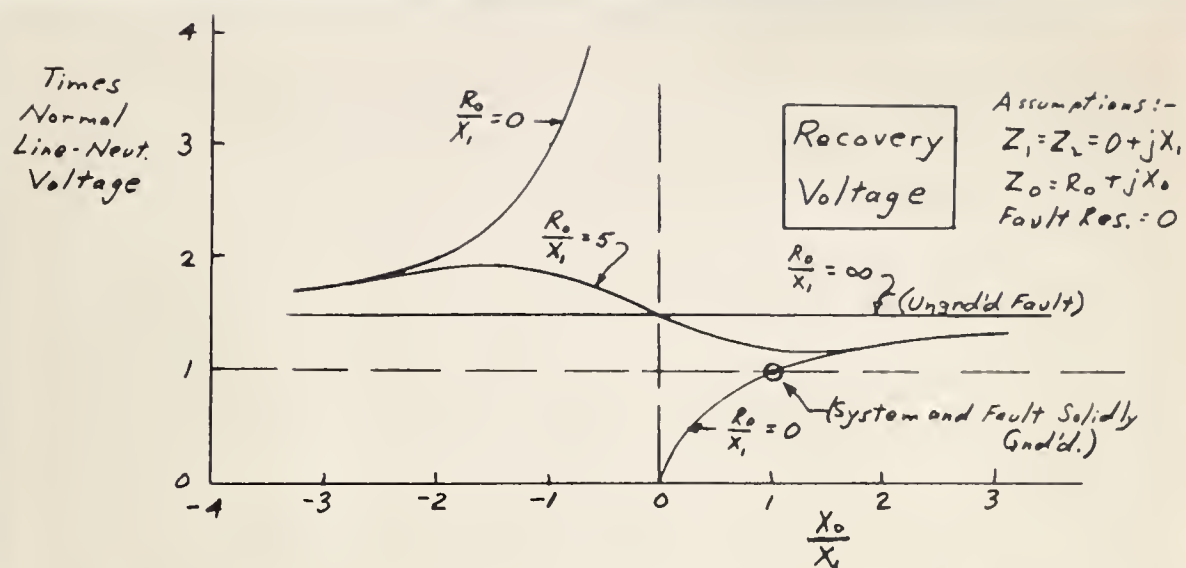


Fig. 15 - Recovery Voltage across First Phase to Clear for a 3L-G Fault

Chapter IV - EQUIVALENT CIRCUITS FOR LINES, GENERATORS, AND TRANSFORMERS

At high frequencies, equivalent circuits for network elements become different and more complicated than they would be at the power frequency. Each element has:

Resistance:- Either ignored or power frequency value used, since its effect(damping) is not large. It is sometimes considered important where underground cables are involved.*

Capacitance:- Power frequency values are correct, but the particular values required are often unavailable.

Inductance:- Iron-cored equipment has, in general, a lower inductance to high frequencies than to the power frequency.

There follows a consideration of the main power system elements in turn.

A. Lines

The mathematical treatment of the behaviour of a transient on a "long line" has been treated by many authors.⁺ It is suggested here that the normal nominal pi-line is suitable and accurate enough for the majority of cases.

*See Ref. No.1, page 94.

⁺See Ref. No.1, page 38.

This conclusion is based on the following investigations:

A long line is defined, in power frequency studies, as one in which for accurate results capacitance of the line may not be divided by two and lumped at the ends of the line. (A pi-line can still represent the line exactly, at 60 cps, if correction factors are applied). The long line "effect" varies inversely as the frequency. Thus if a 100 mile line is a "long" line at 60 cps, then a one mile line is "long" at 6000 cps. Therefore we can say that for high frequency transients, all lines are long. However, the error involved in using a nominal pi-line is not as large as might at first be expected.

A long line subjected to an electrical disturbance has many natural frequencies. The lowest of these is the dominant one (highest amplitude) and is called the fundamental natural frequency. It is given by

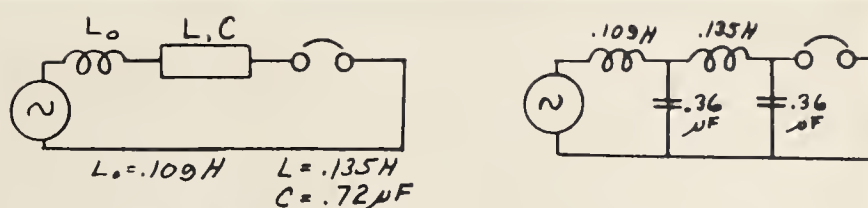
$$f = \frac{1}{4\sqrt{LC}}$$

The line's nominal-pi representation would have a single natural frequency given by

$$f = \frac{1}{2\pi\sqrt{L\frac{C}{2}}} = \frac{1}{2\pi\sqrt{LC}}$$

The ratio of the two frequencies is therefore $4/\sqrt{2\pi}$, i.e., an error of -10%. When the line is combined with

other circuit elements, the error becomes even less. To illustrate: a circuit in which a source with inductance L_0 feeds a fault through a long line, is shown in Figure 16.



(a) Cot. with
"Long Line"

(b) Cct. with
Pi-Line

Fig. 16 - Comparison Calculation

The results are: Exact Calculation:- (Fig. 16a)

$$\begin{aligned} f_1 &= \underline{483 \text{ cps}} \quad 80\% \text{ amplitude} \\ f_2 &= 1790 \text{ cps} \quad 8\% \text{ amplitude} \\ f_3 &= 3300 \text{ cps} \quad 2\% \text{ amplitude} \\ f_4, f_5, \dots &\text{higher freq.'s of small amplitude.} \end{aligned}$$

Pi-line Calculation:- (Fig. 16b)

$$\begin{aligned} f_R &= \underline{474 \text{ cps}} \quad 96\% \text{ amplitude} \\ f_S &= 1180 \text{ cps} \quad 4\% \text{ amplitude} \end{aligned}$$

Thus the frequency error due to using a nominal pi-line is only 2%, and the amplitude error is less than it appears to be (20%) since in the real line the higher frequencies add to the fundamental to give a peak higher than 80%.

Another point is that lines usually have considerable capacitance-to-ground compared with other circuit elements and therefore contribute lower frequency components to the

transient. If the severest voltage transient condition (as opposed to severest fault current condition) is being sought, the lines should therefore be disconnected from the bus.

If an open-circuited line is "hanging on a bus" (i.e. not feeding fault current) its total lumped capacitance may be used to represent it.

When unsymmetrical conditions exist, the three phases of a line should all be represented, as for the case outlined in Chapter VII.

B. Generators

(a) Inductance:- It has been found that the high frequency inductance of generators is about 80% of the value given by the subtransient reactance.

(b) Capacitance:- For normal purposes, the capacitance per phase given by the manufacturer is used and may be considered as lumped at the ends of the windings. In other words, a star-connected machine would have $\frac{1}{2}(C/\text{phase})$ at its terminals and a delta-connected machine, C/phase .

Generators are sometimes considered as long lines for high frequency purposes-- especially for faults at their terminals.

C. Transformers

Although Hammarlund has gone into extreme detail to find complicated equivalent circuits for transformers, a method used by Adams* seems to be adequate. His method is to lump the winding capacitances at the winding ends, and use the normal power frequency reactance to calculate inductance. See Figure 17.

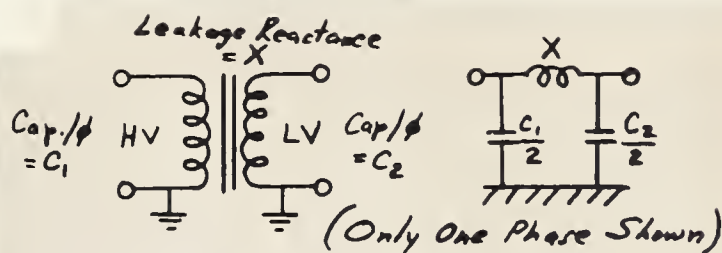


Fig. 17 - Transformer Representation

*See Reference No. 4.

Chapter V - LIMITATIONS OF THE CONTRAVES NETWORK ANALYSER COMPONENTS AT HIGH FREQUENCIES

The analyser passive components consist of resistance, capacitance and inductance. High frequency effects which have been investigated are as follows:

A. Inductance of Resistance Units

The reactance of resistance units was found to be negligible, even at high frequencies. Furthermore, resistance units are seldom used in these studies, except as fault or ground resistance, since the inherent resistance of the reactance units provides realistic damping.

B. Capacitance-to-Ground of R-X and Generator X Units

A capacitance-measuring bridge was used to measure capacity-to-ground with results as follows:

R-X Unit.....	600 μ F = .1%
Generator X Unit.....	900 μ F = .15%
Additional internal wiring capacitance....	200 μ F = .03%

(Above readings checked at 10kc and 100kc.

Percentages are on the analyser base.)

These capacities are small compared with the Capacitance Unit values which will be in parallel with them. Capacitance Unit values must be kept above a minimum of 1% as outlined in the next section.

C. Distributed Capacitance of X Units

Here, a real problem arises, but measures can be taken to circumvent it, as will be seen.

A coil having distributed capacitance has an approximate equivalent circuit as shown in Figure 18.

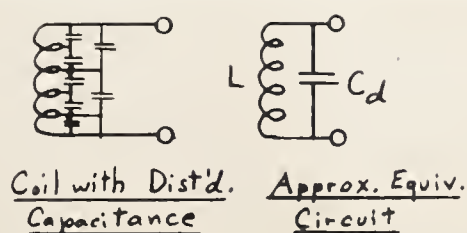


Fig. 18 - Coil Equivalent Circuit

The actual coil will resonate at a frequency which may be used to calculate C_d . "L" is the inductance measured at low frequencies. Resonant frequencies for different tap settings of different coil types (there are six coil types on the Contraves Analyser) have been measured and are tabulated below:

Resonant Frequencies of X Units

<u>x0.1 Unit</u>		<u>x1 Unit</u>		<u>x10 Unit</u>		<u>x100 Unit</u>		<u>x100 Unit</u>	
1.0%	220kc	11%	64kc	110%	17.4kc	1100%	4.95kc	500%	6.4kc
.9	225	10	64	100	17.8	1000	5.00	400	6.5
.8	230	9	65	90	18.5	900	5.05	300	6.7
.7	235	8	66	80	19.0	800	5.07	200	6.8
.6	245	7	67	70	19.5	700	5.10	100	7.0
.5	255	6	68	60	20.1	600	5.20		
.4	265	5	70	50	20.8	400	5.28	<u>x1000 Unit</u>	
.3	280	4	72	40	21.6	300	5.30	2000%	3.1kc
.2	295	3	73	30	22.4	200	5.35	1000%	3.2kc
.1	310	2	74.5	20	23.2	100	5.40		
		1	75.5	10	24.1				

A coil can have a distorting effect on a transient solution when the solution contains a frequency near the resonant frequency of the coil. To study this effect, consider the circuit of Figure 19.

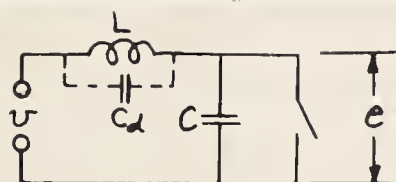


Fig. 19 - Circuit for Analysis of C_d Effect

Solution by Laplace Transforms yields:

$$e = v \left[1 - \left(1 - \frac{C_d}{C+C_d} \right) \cos \left(\frac{1}{L(C+C_d)} t \right) \right]$$

Thus C_d introduces a frequency error and an amplitude error.

The frequency error is $100 \frac{C+C_d - C}{C} \%$ or approximately $50 \frac{C_d}{C} \%$,

and the amplitude error is approximately $100 \frac{C_d}{C} \%$. Assuming

that we can tolerate 5% frequency error and corresponding

10% amplitude error, we must arrange for $C_d/C = 0.1$. Thus

if the coil resonant frequency is $f_R = \frac{1}{2\pi\sqrt{LC_d}}$ and the

circuit resonant frequency should be $f = \frac{1}{2\pi\sqrt{LC}}$ within

5%, a particular coil of resonant frequency f_R may be

used for circuit frequencies up to f_C , where

$$f_C = \frac{1}{2\pi\sqrt{L \cdot 10C_d}} = \frac{1}{\sqrt{10}} f_R \doteq \frac{1}{3} f_R$$

Since L is known and f_R has been measured for all coils

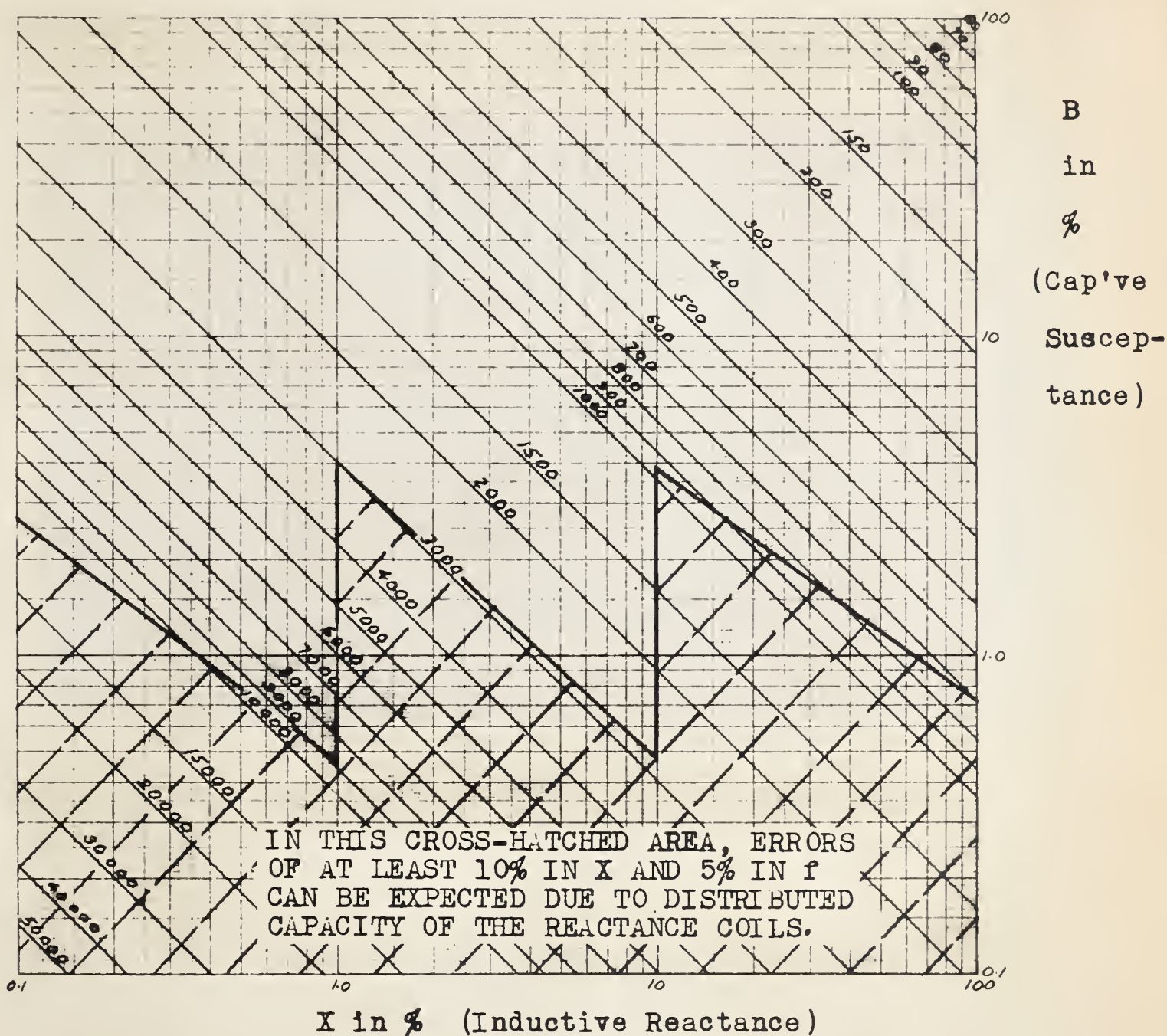
and their tap settings, the permissible highest operating frequencies can be plotted on a chart. See Figure 20.

It is interesting to note that if capacitance units are never set below about 2% the problem of distributed capacity in coils is automatically minimized.

RESONANT FREQUENCY CHART

Frequency in cycles per second
for quantities given in per cent
on any 60-cycle MVA and KV base.

$$f = \frac{60 \cdot 100}{\sqrt{X\% \cdot B\%}} = \frac{60 \cdot 100}{\sqrt{L\% \cdot C\%}}$$



Note: Frequencies read from this chart must be
multiplied by $\frac{500}{60}$
if actual Analyser frequency is required.



EXPERIMENTAL EQUIPMENT
(Refer to Figure 21)



NETWORK
ANALYSER

FREQUENCY
CHANGER
with

480cps	TRIGGER
PHASE	PHASE
SHIFTER	SHIFTER

SYN-
CHRONOUS
SWITCH

AMPLI-
FIER

OSCILLOSCOPE

Chapter VI - USE OF A SYNCHRONOUS SWITCH

A. Description

A synchronous switch is a device for applying a fault and then interrupting it, at any point on an A.C. wave, in order to facilitate viewing of the fault application or interruption on an oscilloscope. The analyser set-up for studying restriking transients was as shown in

Figure 21.

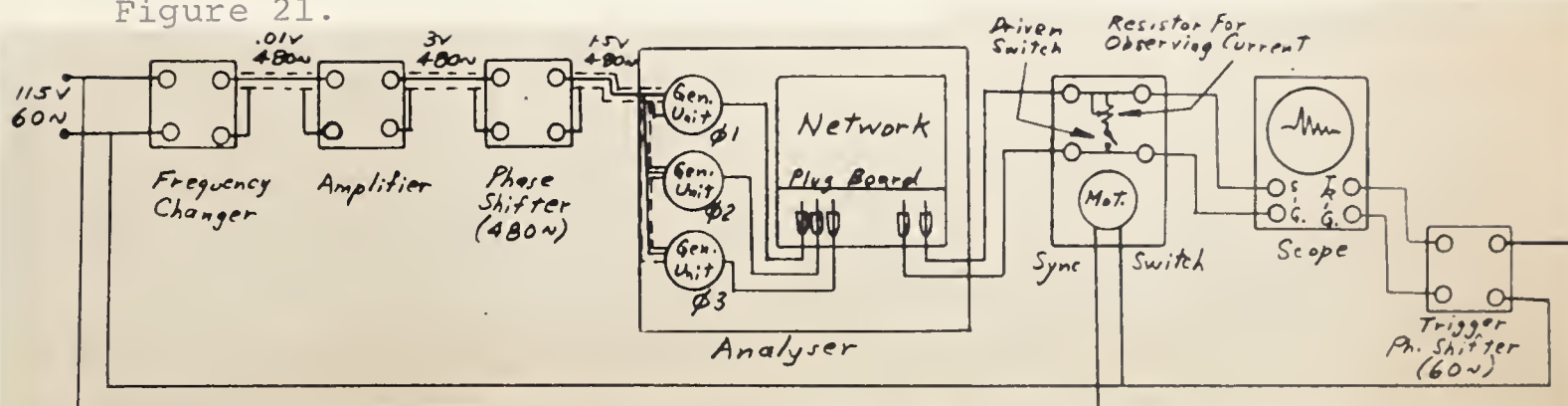


Fig. 21 - Experimental Layout

The synchronous switch constructed by the author is basically two carbon brushes, riding on a brass commutator driven by a synchronous motor at 1800 r.p.m. The brushes are shorted for three-quarters of a revolution and open-circuited for one-quarter. (This can be reversed if desired) The sequence of events for one switch revolution is shown in Figure 22.

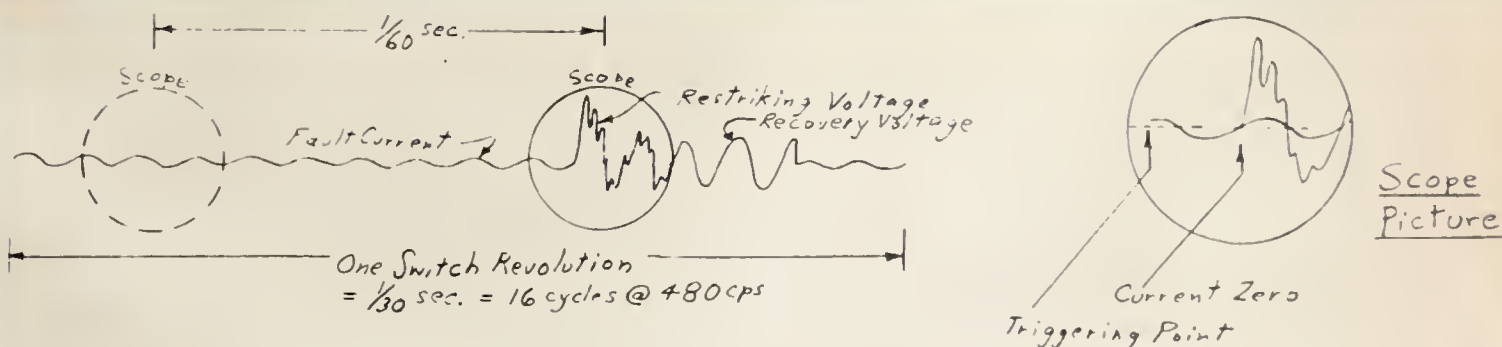


Fig. 22 - Illustrating Sequence of Events

The adjustment of the "Fault Current Resistor" in series with the switch allows fault current as well as restriking voltage to be viewed on the oscilloscope. This resistor should be kept very small (zero, ideally) though, since it affects the network characteristics. The best way to ensure that interruption is occurring at a current zero is to adjust the 480 C.P.S. or generator unit phase shifter until a minimum amplitude transient appears on the scope.

Since the synchronizing signal reaches the scope every $1/60$ second, and the phenomenon repeats only every $1/30$ second, the scope picture is "doubled-up" as shown in Figure 22. When the fault current resistor is reduced to zero, a convenient zero trace results.

B. Development Details

At first glance, the use of 480 c.p.s. as a working frequency instead of the analyser's standard frequency of 500 c.p.s. may appear unusual. The reasons for choosing this frequency were based on the following considerations:

(1) The chosen frequency has to be synchronized with the synchronous switch, in order that interruption will occur at exactly the same electrical angle every time.

(2) The generator unit amplifiers, and especially the generator unit phase-shifters, are designed for 450 to 550 c.p.s. operation. The frequency used should therefore be within these limits.

(3) The motor available was a hysteresis-type synchronous motor, rated 115 volts, 60 c.p.s., 1800 r.p.m., 1/12 HP.

Consideration was given to 10-to-1 "frequency splitting" a signal from the analyser 500 c.p.s. master oscillator and amplifying the resulting 50 c.p.s. to drive the motor. This was found to be impractical, since even though the motor could be run with 100 watts at 50 c.p.s., its starting current was very high. Thus an amplifier would be too large and expensive.

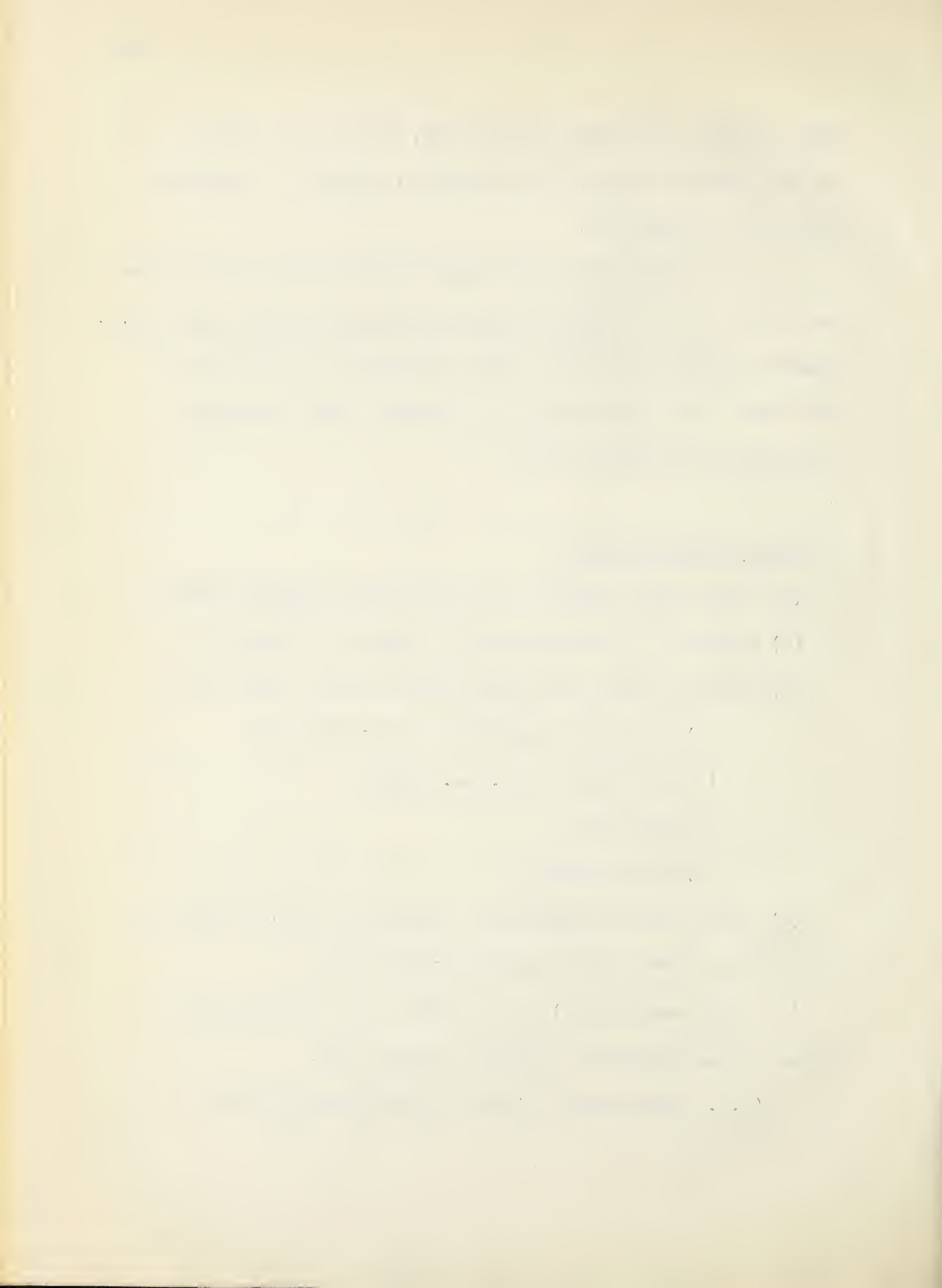
The adopted plan was to drive the motor directly from the 60 c.p.s. supply, and "frequency-multiply" a 60 c.p.s. signal to 480 c.p.s. This was done by rectifying a 60 c.p.s. signal, feeding the resulting harmonic-rich wave shape into a highly selective filter tuned to 480 c.p.s., and amplifying to a voltage high enough to feed to the analyser. It was found that 480 c.p.s. is close enough to 500 c.p.s. that the amplifiers, meters, and phase-shifters function without detectable error.

(The Q-meter is probably inaccurate, but is not useful in the studies anyway.) The resulting repetitive sequence is shown in Figure 22.

It should be noted that from a problem calculation point of view, the analyser base frequency is still 500 c.p.s. since R-X and C units have been calibrated in per cent on that base. The significance of analyser base frequency is outlined in Chapter VII.

B. Instructions for Use

- (a) "Plug" the network on the analyser plugging board.
 - (b) Connect up the apparatus as shown in Figure 21.
 - (c) Turn the amplifier gain control down; then turn on
 - (1) Analyser (generator unit amplifiers)
 - (2) 115-volt, 60 c.p.s.-supply
 - (3) Amplifier
 - (4) Oscilloscope
 - (d) Clean switch commutator, preferably with a fine file, by driving it with the brushes slackened off.
 - (e) With generator(s) set at 100%, turn the amplifier up until the generator voltage is about 10%.
- (N.B.- Generator voltages higher than about 20%



usually cause excessive fault currents and sparking at the switch brushes. The restriking transient amplitude calibration will vary with this setting but the wave shape will be unaffected.)

(f) Rotate the switch commutator by hand to its open position, and adjust the scope controls so that the 480 c.p.s. recovery voltage appears on the screen.

(g) Turn on the synchronous switch motor and adjust the scope trigger phase shifter and/or scope trigger plus-minus control until the transient appears.

(h) Adjust the 480 c.p.s. phase shifter to give interruption at a current zero (minimum transient amplitude) or other desired point of interruption in the wave.

(i) Observe (or photograph) the frequency and amplitude of restriking voltage. For amplitude and frequency calibration purposes, revert to step (f) i.e., normal recovery voltage wave on scope.

Certain frequency and amplitude correction factors will have to be applied to the result, as outlined in the following Chapter.

The first part of the paper discusses the importance of maintaining accurate records of all transactions. It is essential for the business to have a clear and concise record of all income and expenses. This will allow the business to track its financial performance over time and identify areas where it can improve its efficiency. The second part of the paper discusses the importance of maintaining accurate records of all assets and liabilities. This will allow the business to track its net worth over time and identify areas where it can improve its financial position. The third part of the paper discusses the importance of maintaining accurate records of all taxes paid. This will allow the business to track its tax liability over time and identify areas where it can improve its tax position. The fourth part of the paper discusses the importance of maintaining accurate records of all debts. This will allow the business to track its debt liability over time and identify areas where it can improve its debt position. The fifth part of the paper discusses the importance of maintaining accurate records of all equity. This will allow the business to track its equity position over time and identify areas where it can improve its equity position. The sixth part of the paper discusses the importance of maintaining accurate records of all other financial information. This will allow the business to track its overall financial performance over time and identify areas where it can improve its financial position.

Chapter VII - GENERAL PROCEDURE, ILLUSTRATED BY NUMERICAL
EXAMPLE

There are three important conditions which must be met in arranging a practical problem for solution with the analyser and synchronous switch.

(1) Per cent values must be chosen such that resonant frequencies of the X-units will have negligible effect on the solution.

(2) Per cent values must be chosen such that it is physically possible to set them on the board, i.e., values less than 0.1% cannot be set.

(3) The per cent series inductive reactance limiting the fault current should be high enough so that excessive current is not drawn even though reduced voltage is being used.

The following example illustrates these problems. This example was taken from page 86 of reference no.1, and represents an actual condition on the Swedish power system, and for which oscillograms were taken by means of a "current-surge injector". The two dominant frequencies were found to be about 6700 c.p.s. (70% ampl.) and 31,000 c.p.s. (20% ampl.). These values can be compared with the results of the example which follows.

THE HISTORY OF THE UNITED STATES OF AMERICA

BY JAMES M. SMITH, LL.D.,
OF THE UNIVERSITY OF CHICAGO.

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Postage paid at
New York, N. Y.,
and at additional mailing
offices.

The system and breaker under study are shown in Figure 23.

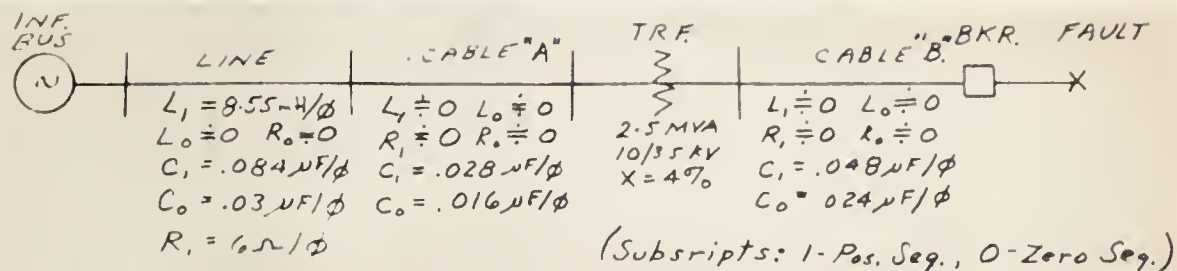


Fig. 23 - System with Positive and Zero Sequence Quantities Shown

Procedure

1. Convert all values to breaker voltage base.

Line

$$L_1 = 8.55 \frac{(3.5)^2}{(10)^2} = 1.05 \text{ mH/phase}$$

$$C_{L-G} = .03 \frac{(10)^2}{(3.5)^2} = .245 \mu\text{F/phase}$$

$$C_{L-L} = \frac{1}{3}(.084 - .03) \frac{(10)^2}{(3.5)^2} = .147 \mu\text{F/phase}$$

$$R_1 = 6 \frac{(3.5)^2}{(10)^2} = .735 \text{ ohms/phase}$$

Cable A

$$C_{L-G} = .016 \frac{(10)^2}{(3.5)^2} = .13 \mu\text{F/phase}$$

$$C_{L-L} = \frac{1}{3}(.028 - .016) \frac{(10)^2}{(3.5)^2} = .0236 \mu\text{F/phase}$$

Cable B

$$C_{L-G} = .024 \mu\text{F/phase}$$

$$C_{L-L} = \frac{1}{3}(.048 - .024) = .008 \mu\text{F/phase}$$

Transformer

$$L = \frac{.04 \times (3.5)^2}{2\pi \times 60 \times 2.5} = .52 \text{ mH/phase}$$

2. Sum the inductances (reactances) limiting the fault current.

$$L_{\text{TOTAL}} = 1.05 + 0.52 = 1.57 \text{ mH.}$$

3. To keep fault current down to 400% at 20% voltage, L_{TOTAL} must be 5% or more. Thus calculate Base L.

$$1.57 \text{ mH} = 5\%. \text{ Therefore, } \underline{\text{Base L} = 32 \text{ mH}}$$

4. Calculate lowest isolated L in circuit, in per cent.

This must be 0.1% or more. If smaller, increase by decreasing Base L.

$$L = \frac{.52}{32} = 1.62 \% \text{ which is acceptable.}$$

5. From Figure 20, find the corresponding lowest permissible isolated C of the circuit.

$$\text{For } L = 1.62 \%, C = 3\% \text{ (approx.)}$$

6. With minimum isolated C of circuit equal to this value, calculate a convenient Base C.

$$C = .008 \text{ } \mu\text{F/phase} = 3\%. \text{ Therefore let } \underline{\text{Base C} = .351 \mu\text{F}}$$

(This value gives
a convenient
Base Frequency)

7. Calculate the Base Frequency.

$$f = \frac{1}{2\pi \sqrt{.032 \times .351 \times 10^{-6}}} = 1500 \text{ c.p.s.}$$

$$\underline{\text{Base Frequency} = 1500 \text{ c.p.s.}}$$

Since analyser base frequency is 500 c.p.s., all observed frequencies must be multiplied by K, where $K = \frac{\text{Base } f}{500}$.

$$K = \frac{1500}{500} = 3 \quad \underline{K = 3}$$

8. Evaluate all L's and C's on these bases.

$$(\text{Base } R = 2\pi \times \text{Base } L) \times (\text{Base } f)$$

Line

$$L_1 = 3.3\% \quad C_{L-G} = 70\% \quad C_{L-L} = 42\% \quad R_1 = 6\%$$

Cable A

$$C_{L-G} = 37\% \quad C_{L-L} = 42\%$$

Cable B

$$C_{L-G} = 6.8\% \quad C_{L-L} = 3.2\%$$

Transformer

$$L = 1.6\%$$

The resulting circuit diagram, ready for plugging, is shown in Figure 24.

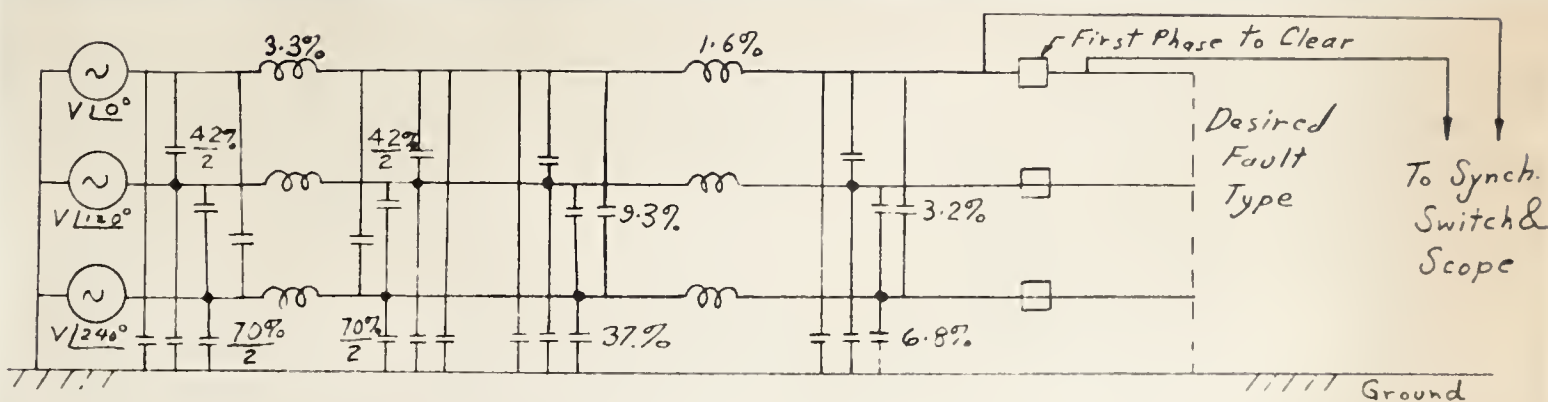


Fig. 24 - Analyser Set-up

This problem has been set up as a three-phase problem, with one generator unit representing each phase. It has been found that the phase-shifters of the units are still accurate at 480 c.p.s., so that the three can be set 120°

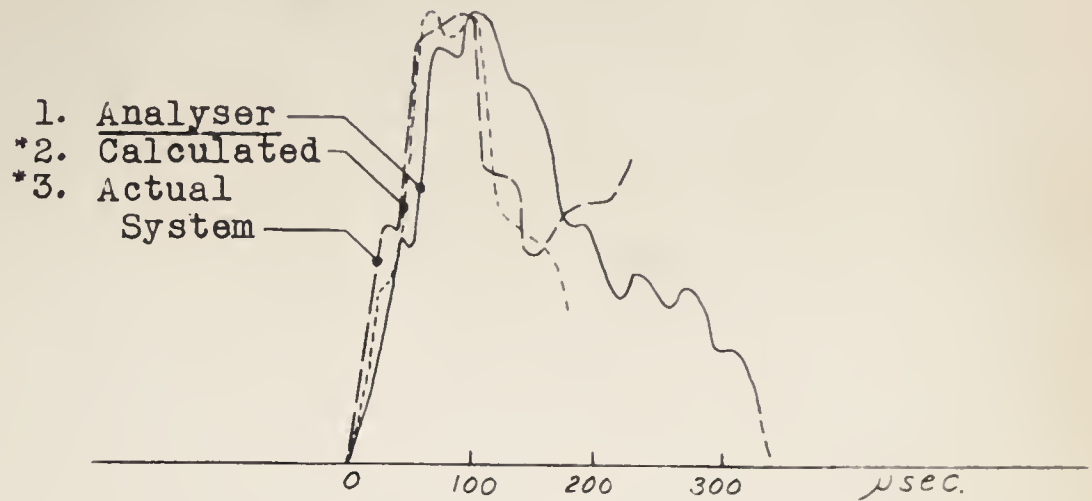
apart by this means. This method is generally simpler than the use of symmetrical components, in solving transient unbalanced fault problems. Sometimes, as for example for a three-phase-to-ground fault, a single-phase miniature system can be used. However, most L's of the circuit have to be multiplied by $3/2$ and C's by $2/3$. For details, see reference no.1.

Results of the Illustrative Problem

Results are presented in Figure 25.

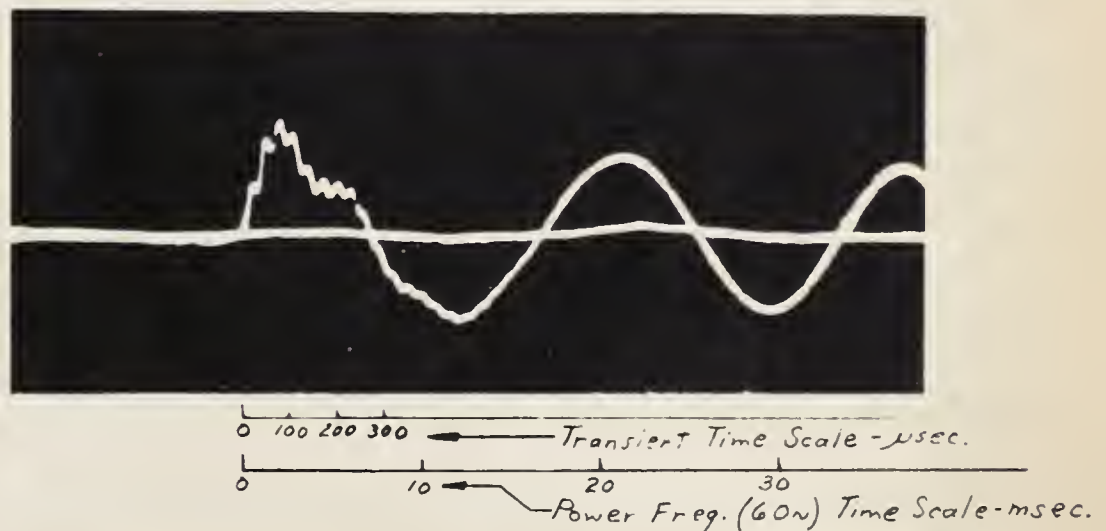
A practical problem of interest is that of experimental equipment grounds. To eliminate 60 c.p.s. pick-up, it was found necessary to ground the oscilloscope chassis to the 60 c.p.s. power mains ground. The analyser frame was then connected to the oscilloscope chassis. Then, in order to simulate an ungrounded three-phase fault, the whole network on the analyser was ungrounded, that is, its generator neutrals, and all capacitors-to-ground, were taken to a separate bus, which was left ungrounded. Thus the system ground was completely separate from the fault ground, which represented, effectively, an ungrounded fault on the system.

First phase to clear.
 Three phase ungrounded fault.
 Interruption at a current zero.
 For the undamped case, (c) below, all resistance removed from circuit in order to determine natural frequencies.



(a) Enlarged Tracing of (b) Compared with Two Other Methods

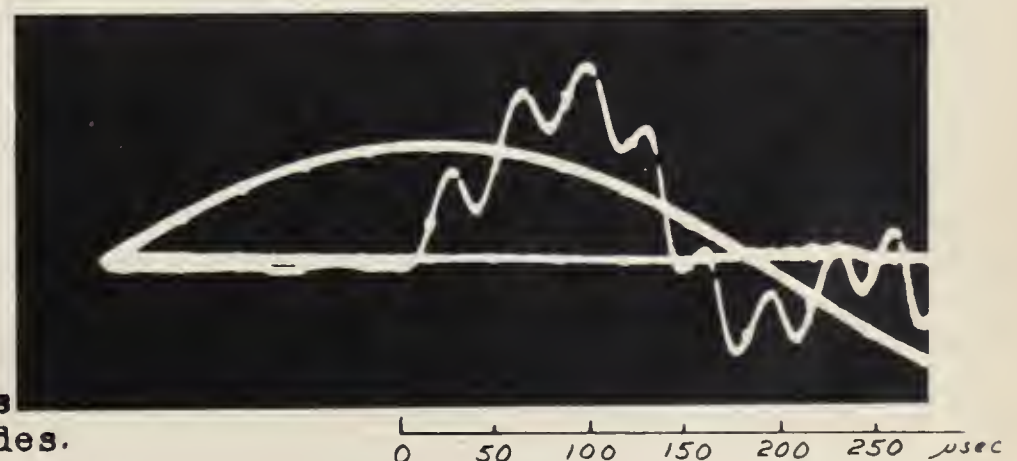
*Curves 2 and 3 taken from Ref. 1, p. 87.



(b) Oscillogram of Damped Transient

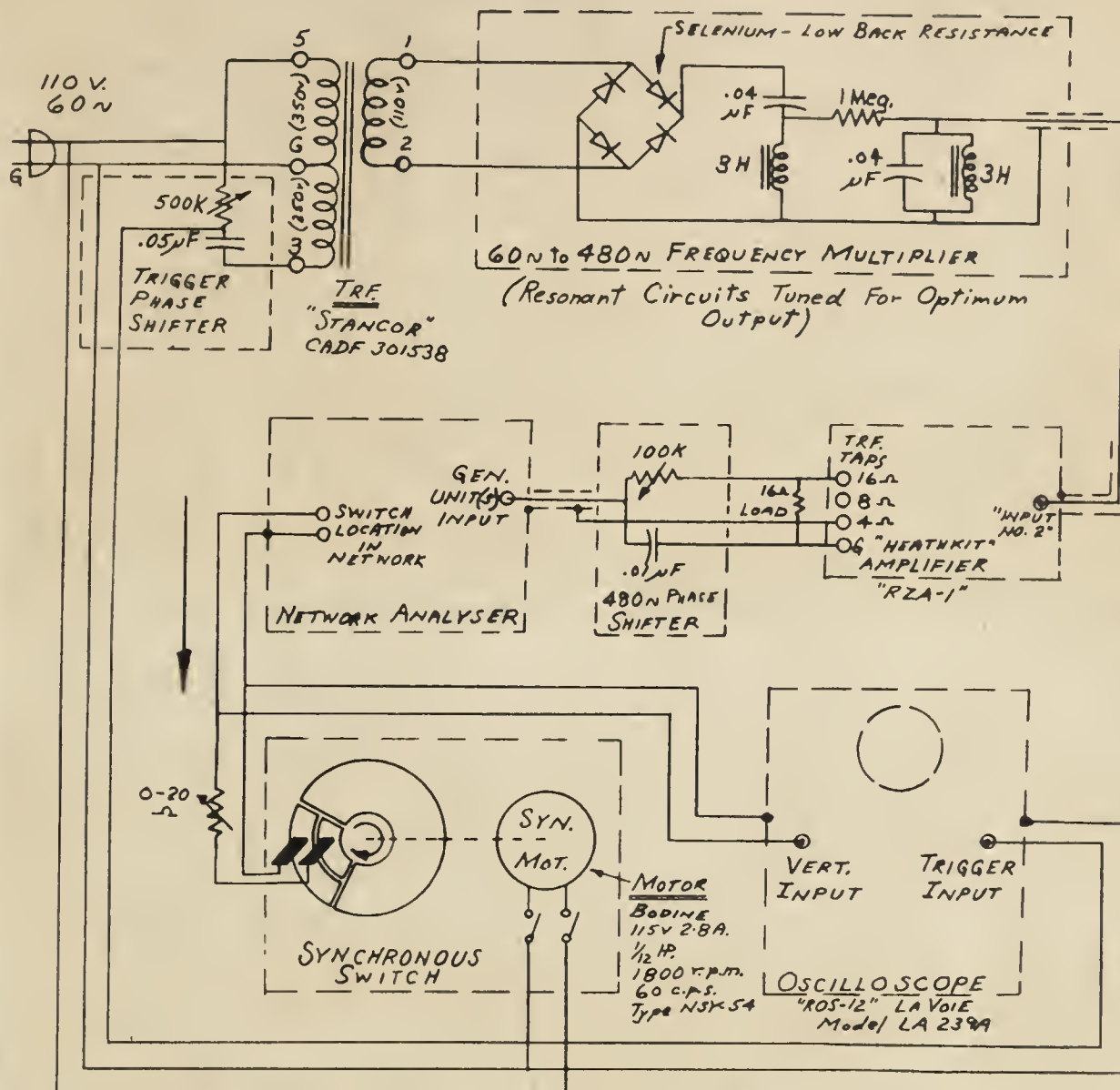
Analysers: $\rightarrow$
 70% 6.0 kc
 30% 30 kc

Calculation:
 70% 6.7 kc
 20% 31 kc
 10% frequencies of minor amplitudes.



(c) Oscillogram of Undamped Transient

Figure 26

EQUIPMENT CIRCUIT DIAGRAM



Chapter VIII - CONCLUSIONS AND GENERAL REMARKS

The University's Contraves Network Analyser may be used for representing a network in miniature for the purpose of studying switching transients. However, certain precautions must be observed, especially with regard to the distributed capacity of the reactance unit coils.

The method used by the author for simulating circuit breaker interruption was by means of a rotating synchronous switch. With care, accurate results could be obtained by this method. However, it is suggested that transistor switching could be used to give more consistent results, since the problems of brush-to-commutator resistance and brush arcing would then be eliminated. Thyatron switching is not suited to this particular analyser since thyatron arc voltage drops would be too high in proportion to the analyser base voltage, 15 volts.

Photographic records were taken by means of a single-lens reflex camera mounted on a bracket fastened to the oscilloscope, and high speed film was used. A superior system would be to use a Polaroid-Land camera, for two reasons. Firstly, the available Polaroid films

are high speed by nature, and secondly, the finished print is almost immediately available so that it may be re-taken if the lens-opening or exposure time, etc. have been misjudged.

In this paper, stress has been laid on the interruption of heavy fault currents. Other problems, such as the interruption of line charging current or transformer magnetizing current are also applicable to the apparatus and methods described. Circuits of academic interest, perhaps in the verification of Laplace Transform solutions could also be studied in this way.



BIBLIOGRAPHY

Note: Most of the following references contain extensive bibliographies. The references listed here have been referred to in this paper.

1. Transient Recovery Voltage Subsequent to Short-Circuit Interruption with Special Reference to Swedish Power Systems

P. Hammarlund, 1946. (Book)

An exhaustive investigation into methods of determining restriking transients by mathematical and current-surge injector means. Analyser methods are mentioned only in one paragraph, but the suggestions given for equivalent circuits for lines, generators, and transformers, etc., are enlightening from the analyser point of view. The last chapter contains a bibliography with summaries. about 200 entries, covering all publications on the subject up to 1946.

2. Circuit Breaking H. Trencham, 1953. (Book)

A series of six lectures by members of the British Electrical and Allied Industries Research Assn. (E.R.A.), covering many phases of the problem.

3. Circuit Breaker Recovery Voltages Park. Skeats. 1931.
AIEE Transactions, Vol. 50, p. 204.

This article was the first American article to present an extensive practical approach to the subject. A great

deal of emphasis is placed on recovery voltage as opposed to restriking voltage.

4. Practical Calculation of Circuit Transient Recovery Voltages Adams, Skeats, Van Sickle, Sillers. 1942. AIEE Transactions. Volume 61, p. 771.

The authors give rules for approximate calculation of restriking transients. They give useful tables for determining inductance and capacitance of typical American power apparatus.

5. Transients in Power Systems Peterson, 1951. (Book)

Chapter 4 deals with the "Miniature System Approach". Many curves are given which can be used to determine recovery voltages under different fault conditions.

6. C.I.G.R.E. Report of Study Committee Number 3 for April 1959.

Reference number 39 as filed in Professor Harle's office at the University of Alberta. This report outlines the latest discussions of the CIGRE Circuit Breaker Committee.

7. Circuit Analysis of A.C. Power Systems E. Clarke. 1943. (Book)



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